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# Guide to Using the Berkeley Lab Cosmic Ray Detector

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## General Information

Cosmic rays are particles that strike the Earth at high speeds, and consequently high energies, from sources within our galaxy and beyond. To measure primary cosmic rays—these particles that come directly from sources in outer space, you would need to travel very high into the Earth's atmosphere. These primary cosmic rays collide with particles in our atmosphere and produce particles called secondary cosmic rays—many of which are muons or electrons. The Berkeley Lab detector measures secondary cosmic rays, which can be found at, and even below, the surface of the earth.

## The Berkeley Lab Detector

A wooden box provides the frame of the detector. A circuit board is mounted, using nuts and the switches on the board, to a Lucite panel. This panel, in turn, is fastened with screws to the wooden box. Two hose clamps hold each photomultiplier tube in place. Each of these tubes is glued to a piece of scintillator, which

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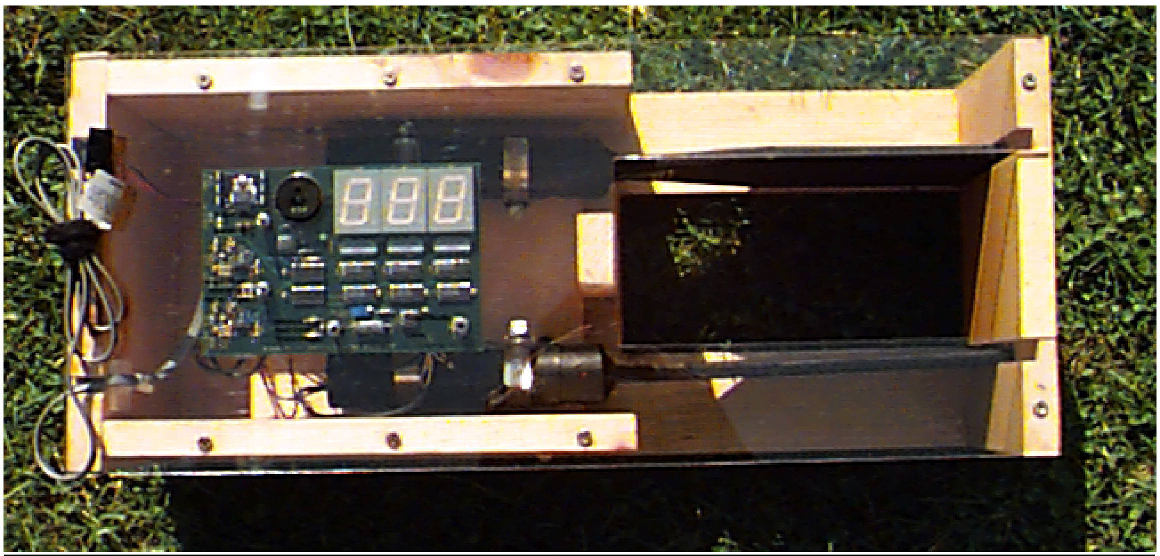
is wrapped in aluminum foil (with the exception of the part of the scintillator touching the face of the phototube) and then covered with cardboard. These prepared pieces of scintillator are called paddles.

The detector requires a 12 V power source to operate. The power source can be a common 12 V transformer, which can be found in many hobby stores, a 12 V outlet from an automobile, or a standard 12 V battery.



## How it Works

When a high-energy particle passes through the scintillator paddle, electrons in the scintillator become excited. The electrons release a flash of light, and return to their ground state. The light, a few photons, hits the photocathode of the photomultiplier tube.

Inside the phototube is a photocathode, a plate coated with a light sensitive material that has a low work function. Consequently, it does not take much energy input to excite the ion enough for it to release an electron.

The light from the scintillator strikes the photocathode and produces an electron. This electron travels (because of a voltage potential difference built into the phototube) to another coated plate and knocks of several more electrons. These electrons continue and strike another plate, each releasing still more electrons. This process continues, plate after plate, until there are a sufficient number of electrons to produce a several hundred-millivolt signal.

Unfortunately, the phototubes are so sensitive that there is a phenomenon, which is called “phototube noise”. For example, thermal energy can cause an electron to “boil off” of one of the ions. Then the electrons continue along, exciting other electrons, as before, and creating a signal. To minimize this noise, two paddles are used “in coincidence”. This means that if both paddles register an event very close together within a very short period of time, it is counted as a cosmic ray.

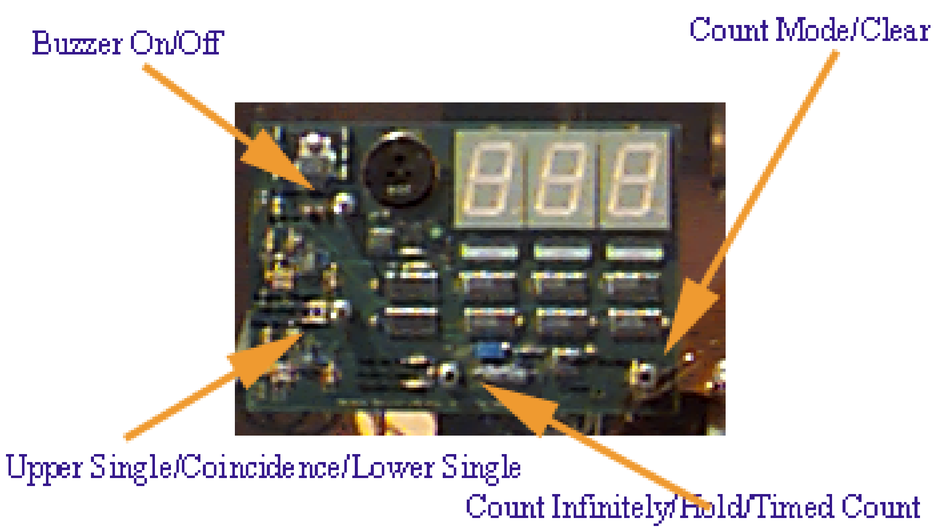
The circuit board, which contains the simple coincidence logic, compares the inputs from each photomultiplier tube and determines which meet the criterion for an event. The board keeps track of these counts and displays them. Since the noise counts are random in time, they do not produce a coincident count. This detector requires that hits in each paddle occur within 800 nanoseconds or $8 \times 10^{-7}$ seconds.

## Operating the Detector

To turn the detector on, connect it to a power source by inserting connecting the transformer to a plug and inserting the other end into the connector. The display numbers will light up. You control the detector with the four switches as follows:

**Buzzer On/Buzzer Off** When in the "Buzzer On" position, the buzzer will beep each time the detector records another count. It will beep whether the detector is in counting mode or not, provided the detector is on. "Buzzer Off" deactivates it.

**Count Infinitely/Hold/Timed Count** With "Count Infinitely", the detector continues to count until the switch is moved to the "Hold". Then it displays the last count. You may count past 999 if you keep track of the thousands digit yourself—the numbers roll over to 000 and continue counting. "Timed count" stops counting after 60 seconds and then continues to display the count up to that time. After you have started a timed count, the detector cannot be reset without turning the power off. To do another timed count, you must wait until the clock stops.




**Upper Single/Coincidence/Lower Single** "Coincidence" counts cosmic rays when the detector is counting by the principles explained in the section entitled "How it Works."

"Upper Single" and "Lower Single" will increment the count any time a particle with enough energy passes through the selected scintillator. Phototube noise can also result in counts. Using the single modes, you can demonstrate the existence of background noise and the necessity of the coincidence circuit.

**Count Mode/Clear** The upper position is "Counting Mode".

This means that the detector will display counts. The lower position is "Clear." This zeros the display. The detector will not display counts if the switch is left in the "Clear" position. Additionally, clearing the display does not stop the time on timed count. The count will remain at zero as long as the switch is in the clear position, and it will continue counting if it is returned to "Counting Mode."

## Changing the Timer with the Adjustable Resistor

The adjustable resistor is used to change the length of time the detector counts when it is set in "Timed Count" mode. Use a small screwdriver to adjust this resistor, which is located at R24. To set it to 60 seconds, you need to time it, adjust it, and time it again. The screw can complete 20 full turns. To get an idea of how many turns you need, determine the time change in one turn to find approximately how many turns you need to arrive at 60 seconds. Then make finer adjustments.

## Determining Average Count Rate and Error

### Sample data

The cosmic ray detector was oriented with its paddles parallel to the ground. In this geometry, it measured vertical cosmic rays. Each trial was for 65 seconds.

| Trail | # of Counts |
|---|---|
| 1 | 110 |
| 2 | 141 |
| 3 | 97 |
| 4 | 106 |
| 5 | 115 |
| 6 | 118 |
| 7 | 121 |
| 8 | 121 |
| 9 | 110 |
| 10 | 125 |
| Total | 1160 |

## How to calculate the rate

The total number of counts, N, is then 1160 counts in 10.8 minutes The error, or sigma, $\sigma$, can be calculated by taking the square root of N.

N = 1160 counts divided by 10.8 min = 107 counts/min

$\sigma = \sqrt{1160}$ counts divided by 10.8 min = 3.2 counts/min

So, the average count rate = 107 ± 3 counts/min

## Alternative Data Collection: Using the TI CBL Digital Probe

The cosmic ray detector collects data—the number of counts per time. One way of acquiring this data is simply by reading the display numbers. Another way to retrieve data is by using the

Calculator Based Laboratory (CBL), a Texas Instruments[2] product. The CBL is a hand-held device, which works in conjunction with Texas Instruments' graphing calculators. It is designed for collecting scientific data in the classroom. The calculator sends commands to the CBL via a cord, which is included with the calculator. The data is sent to the CBL from the board through Texas Instruments' custom probe created for the CBL. The CBL can be used to keep track of time while counting cosmic ray events.

You need programs so that the Texas Instruments calculator can communicate with the CBL. Below are programs[3] written for a TI-83. Press *Program*, select *New*, and enter the name of the program. Then, input these programs.

If you have never programmed this calculator before or if you do not know where to find the functions (such as Get, Prompt, min, or Pause) called in the following programs, consult the book accompanying your calculator. To make "→", use the STO→ (store) key.

Enter the program *TIME* into your calculator before *COUNTMAX* or *NCOUNTS* because the latter two programs need to call *TIME* in order to work.

It is not possible to write a program, which tells the CBL a time and then returns the number of counts in that time. Therefore, this program utilizes a different approach by telling the CBL there will be 512 counts. The CBL can then be asked to return the time. This program calls *TIME*, which follows, and will not work unless *TIME* has also been input. You will get an incorrect value for the time if you do not wait until the CBL has finished getting the

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[2] More information can be found at Texas Instruments' web page at http://www.ti.com/calc/docs/cbl.htm.

data—displays "DONE"—before you press enter. In addition, press the *Enter* key at the end of the program after you have recorded the time. If you look at L1 after executing this program, you can get a list of the times each cosmic ray event occurred.

Program named TIME:

```
:Get(L1)
:Get(L1)
:L1→ CRAY
:max(LCRAY)-min(LCRAY)→ A
:ClrHome
:Output(1,1,"TIME")
:Output(2,1,A)
:Output(4,1,"SECONDS")
:Pause
:ClrHome
```

Program named COUNTMAX:

```
:Send({0})
:{1,1,2}→ L6
:Send(L6)
:{3,0,512,3,21,2,0,0,1)→ L6
:Send(L6)
:ClrHome
:Output(1,1,"PRESS ENTER")
:Output(2,1,"AFTER CBL IS")
:Output(3,1,"DONE")
:Pause
:prgmTIME
```

If you want flexibility with the number of counts you use, try *NCOUNTS*. It allows the user to choose the number of counts. This number must be a positive integer less than, or equal to 512. If you do not, the CBL will return an error.

Program named NCOUNTS:

```
:ClrHome
:Output(2,1,"NUMBER OF COUNTS")
:Output(5,1,"NOT>512")
:Prompt N
:{1,1,2}→ L6
:Send(L6)
:{3,0,N,3,21,2,0,0,1)→ L6
:Send(L6)
:ClrHome
:Output(1,1,"PRESS ENTER")
:Output(2,1,"AFTER CBL IS")
```

[3] Slight modifications may have to be made for the other calculators.

```
:Output(3,1,"DONE")
:Pause
:prgmTIME
```

Attach the calculator to the CBL with the appropriate cord, making sure the cord is firmly pushed in. Plug the CBL cord into the "DIG IN" channel. Turn on the CBL and calculator. Connect the cosmic ray detector to a power source. *The cosmic ray detector does not have to be in "count mode" when you are taking data with the CBL.* Execute *COUNTMAX* or *NCOUNTS*. The CBL should display "READY" and then "SAMPLING". When it shows "DONE," press enter to retrieve the time.

## Things to Try

Compare the count rate of the detector with the paddles parallel and then perpendicular to the ground.

Compare the count rate of the detector with a large slab of metal between the paddles and without.

Measure the cosmic ray flux at different elevations. Take the detector to the lowest location near you. Then take it to the highest elevation in your area. Make sure that you take enough data so that you have sufficient accuracy to measure the difference count rate in the different locations.

## Acknowledgements

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is located in Rockaway New Jersey. They very graciously donated half of the phototubes that we produced. Their support enabled us to produce twice as many complete detectors. Some of the background information on cosmic rays was based on information provided by Ed Iskander.

# Appendix 1 Background on Cosmic Rays

Primary cosmic rays are the particles originating from astrophysical sources. As such, electrons, protons, helium, carbon, oxygen, and iron are included in this particle spectrum; they are all readily found within stars. Some primary cosmic rays are the result of solar flares that are intense disturbances on the surface of our sun. Other cosmic rays are the result of exploding supernovae. When these late-staged stars collapse, they launch particles into space at nearly the speed of light.

Secondary cosmic rays are particles that result from the interaction of primary cosmic rays and particles in our atmosphere. This composition spectrum includes lithium, beryllium, and boron nuclei. Another result of these collisions is the production of charged mesons, which decay into muons and neutrinos, and uncharged mesons, which decay into electrons and photons.

## Some Possible Decay Reactions

$\mathbf{p + n \rightarrow p + p + \pi^-}$

A proton (p) and neutron (n) collide resulting in two protons and a negatively charged pion ($\pi^-$), a member of the meson family. Then

$\pi^- \rightarrow \mu^- + \nu$

Here, the pion ($\pi^-$) decays into a negatively charged muon ($\mu^-$) and a neutrino ($\nu$). The mean half for this decay is $2.6 \times 10^{-8}$ s.

$$\mathbf{p + n \rightarrow p + n + \pi^0}$$

Another possible scenario is that the collision between the proton (p) and neutron (n) results in a proton, a neutron, and an uncharged pion ($\pi^0$).

$$\pi^0 \rightarrow \gamma + \gamma$$

This pion ($\pi^0$) decays into two photons ($\gamma$). Another name for this energy photon is a gamma ray. The mean life of the $\pi^0$ decay is $8.4 \times 10^{-17}$ seconds. The photons can strike the detector or interact with other nuclei and produce electrons.

Secondary cosmic rays can be produced from proton-proton interactions, just as the proton-neutron reactions that were previously described. Muons and gamma rays are produced from the interactions.

Often, the incoming primary cosmic ray will have sufficient energy for the decay sequences of the resulting secondary cosmic rays to set off new decay sequences. For example, the gamma-ray photons can themselves then produce more electrons, which may again produce more gamma-ray photons, etc. If the incoming primary cosmic ray has enough energy, this process may be repeated many times. Eventually, a huge number of particles can be detected at ground level over an area of many square kilometers. This barrage of particles streaming down through Earth's atmosphere is commonly referred to as an *extensive air shower*.

## Facts about Cosmic Rays

At the surface of the earth, the most plentiful charged cosmic rays are muons.

Cosmic rays even penetrate the earth's surface, and can be detected underground.

Cosmic rays account for approximately 10% of the radiation you receive each year.

People who live around 7000' elevation get about double the dose of cosmic rays than those people who live at sea level.

## Cosmic Ray Detectors Around the World

Cosmic rays are detected in a variety of ways depending upon their energy. Since the lowest energy cosmic rays are easily absorbed by Earth's atmosphere, they can only be detected by equipment aboard satellites, high altitude balloons, and other detectors nearly outside of the atmosphere. As noted above, higher energy cosmic rays interact in the atmosphere producing cosmic ray air showers. Many of these air showers are absorbed in the atmosphere and do not reach ground level. However, the air shower particles initially travel at a speed greater[4] than that of light in the atmosphere and emit tiny flashes of light known as Cherenkov light. This light, analogous to the sonic boom phenomena, is detected by very sensitive detectors on clear nights.

High-energy cosmic rays can be detected at the surface of the earth with particle detectors. Using several detectors in an array, a primary cosmic ray's arrival direction can be determined by using the detectors to pinpoint its location at several different times.

Current research continues on the mysterious and rare high-energy cosmic rays (with energies greater than $10^{17}$eV). Currently,

[4] A particle cannot travel faster than the speed of light in a vacuum. However, light slows in the atmosphere. It is possible for a particle to travel faster than the speed of light in air.

their source and an explanation for their high energies are unknown. One of these detectors is the Fly's Eye,

http://bragg.physics.adelaide.edu.au/astrophysics/HiRes.html ,

detected the highest energy cosmic ray, a single particle with $3.2 \times 10^{20}$ eV (or 51 joules) of energy.

# Appendix 2 CBL Program to Compute Average Quantities

This program, which may be run after collecting data, returns the average time between counts and the standard deviation for this average.

```
PROGRAM:INT
:List(LCRAY)->TIME

:ClrHome
:Output(1,1,"AVG TIME BETWEEN")
:Output(2,1,"COUNTS:")
:Output(3,1,mean(LTIME))
:Output(4,1,"STAN DEV:")
:Output(5,1,stdDev(LTIME))
```